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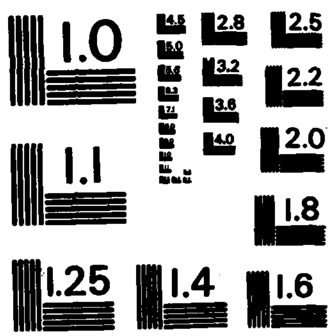

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LASER RAMAN PROBE DIAGNOSTICS

FINAL REPORT
September 1, 1975 through August 31, 1979

Contract 8960-17
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The overall objective of this work is to provide a scientific basis for a new non-perturbing, space- and time-resolved optical probe of gas temperature and constituency in combustion systems. The major part of the effort is focussed on the development of Raman scattering methods to accomplish this goal. Effort is also directed toward the goal of using other compatible measurement techniques (viz., laser velocimetry) in an integrated probe system for flame characterization.

FINAL REPORT - TECHNICAL SUMMARY

This report presents a technical summary of work accomplished under the ONR Sponsorship of Contract 8960-17 to Purdue University, Subcontract under Contract N00014-75-C-1143, N094-405 to the Office of Naval Research.

Abstract

The overall objective of this work is to provide a scientific basis for a new non-perturbing, space- and time-resolved optical probe of gas temperature and constituency in combustion systems. The major part of the effort is focussed on the development of Raman scattering methods to accomplish this goal. Effort is also directed toward the goal of using other compatible measurement techniques (viz., laser velocimetry) in an integrated probe system for flame characterization.

Background

The impact of increased knowledge of the combustion and fluid mechanic properties of modern technological systems for propulsion (such as jet engine combustors, gas turbines, etc.) can be strong from many points of view. Clear need exists for a major thrust for coupling effectively combustion analytical treatments (i.e., for predicting overall combustion system properties from a knowledge of the detailed component processes, via an approximate description or model of the combustion system) with available experimental data. This straightforward approach is of great importance and high potential utility, but is also, in fact, rather difficult to accomplish. One of the largest obstacles to this coupling of efforts is the often inherent separation of research into that related to new physical measurement techniques and that involved with advancing the understanding of a particular field to which the new techniques can be conceivably applied. It is this obstacle which is attacked in the work described here. New developments in optical light-scattering diagnostics are applied to a well-controlled turbulent flame for which data can be obtained of use to analysts in testing modeling procedures.

The specific goal of this portion of our ONR-sponsored research program was to develop the parts of a combustion probe system aimed at characterizing flames by means of detailed temperature, species density, and velocity data. This can be achieved, in principle, by utilizing light-scattering diagnostic techniques, viz., spontaneous Raman scattering to measure the scalar thermodynamic gas properties, and laser velocimetry to determine the velocity flowfield. In practice, in order

to accomplish this goal, potential measurement difficulties must be overcome.

The types of problems encountered in this development work included:

- Background interferences caused by the incident laser beam.
- Background independent of the incident beam.
- Spatial resolution limitations.
- Spectral interferences that limit the specificity of chemical species identifications.
- Experimental limitations of available pulsed laser sources.
- Requirements for characterizing the spectral properties of each laser pulse.
- Difficulties associated with the coupling together of the Raman and laser velocimetry measurement components.

These problem areas were associated with the need to develop the measurement probes selected into techniques capable of producing precise and accurate data for a range of laboratory flames. This requirement provided the driving force for the work described in the next section. Earlier work in the application of Raman scattering and laser velocimetry to fluid flow and combustion problems either had not combined the techniques (so that only a partial description of the system properties resulted), or did not correspond to an experimental configuration which possessed quantifiable properties for system modeling, or was not applied to a hot, reactive system. The significance of the work described here is the progress toward the combination of the Raman and laser velocimetry methods for diagnostics on specific and quantitative reactive flow configurations. The ultimate applications foreseen for the final probe system to be developed are in the coupling between light scattering diagnostic methods and turbulent reacting flows. Such flows - particularly in the areas associated with the interactions between turbulent mixing processes and high temperature flame chemical kinetics - are considered to be in an area of high priority for combustion research and development.

Achievements

The accomplishment of the goals for this research effort has been carried out in two stages. Firstly, laser velocimetry (LV) was applied in a test experiment aimed at studying a specific combustion

problem. The purpose of this work was to explore the operational characteristics of LV in a detailed, well-focussed laboratory program, and to understand better their complexities in connection with our goal of coupling LV to a Raman scattering (RS) diagnostic probe for eventual simultaneous temperature, species density, and velocity data acquisition.

Secondly, a program of several phases was developed to measure (1) temperature by RS techniques; (2) simultaneous values of the majority species density, N_2, from RS data; (3) near-simultaneous values of temperature and fluid velocity from RS and LV data; and (4) detailed data on a product of combustion, H_2O vapor, from RS data. This effort sets the stage for the following phase of ONR-supported work, in which near-simultaneous temperature, product gas, and velocity data are to be acquired, thus providing an integrated probe system for basic flame properties.

Laser Velocimetry Experiments. Laser velocimetry (LV) has been developed further as a combustion probe than has Raman scattering, and is available as a commercially-produced instrument. This is not to say that LV as a measurement tool is completely understood, or even that basic problems do not exist in its implementation (such as LV seeding bias issues), but rather that it is far closer to quantitative tests on well-qualified combustion devices than is Raman scattering (RS). In this spirit, we have studied a particular combustion problem as a test of the applicability of LV to laboratory flame studies, and as a test-bed for obtaining needed information concerning its coordination with RS probe equipment.

The problem studied was the effect of combustion upon the turbulence level in a co-flowing hydrogen-air jet.* This issue was studied in a fan-induced 100-mm inside-diameter glass tunnel, with a concentric thin-wall fuel tube of 2.7 mm inside-diameter producing a jet flow of H_2. Flow disturbances were kept to a minimum, and the flow with and without combustion probed by a dual scatter LV optical system used in a near-backscatter configuration. The volume probed corresponded to a scattering zone of about 0.3 mm diameter and length of 0.5 mm. Alumina powder of 1μm nominal diameter was used as seed, and requirements for injecting this seed into the H_2 and/or air streams were determined experimentally.

Detailed velocity profiles and turbulence intensities (rms turbulent velocity normalized by the mean velocity) were measured both with and without combustion, and the differences between these results analyzed. The primary combustion result obtained was that burning affected the turbulent flow mainly by changing the mean axial velocity, and thereby the axial turbulence intensity. No significant amounts of direct coupling of the combustion process to increased turbulence

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* The LV portions of this work were carried out by J.C.F. Wang (presently at Sandia National Labs, Livermore) and B.W. Gerhold (presently at Phillips Petroleum, Bartlesville, Oklahoma). See Bibliography Section.

intensity were found from these data and their associated analyses. In addition to exploring the quantitative aspects of LV sufficiently to obtain the results just quoted, experience was gained in the ways in which the LV probe could be coupled to the Raman equipment in the work which will be described next.

Raman and Coupled Probe Experiments. As a preliminary to the determination of the temperature field by Raman techniques for the same combustion flows as were studied in the LV experiments, mean values of temperature were found through use of thermocouples.** Resemblences and differences with respect to the LV data were seen, and served as a guide in interpreting further the LV results and in planning the details of the Raman temperature probe studies which followed.

Establishment of the time-resolved RS temperature technique required several difficult experimental tasks, of which the lead one was modification and adaptation of a practical laser source. A Phase-R 2100-B coaxial dye laser was utilized after overcoming a variety of problems related to spectral purity, line narrowing, stable tuning, beam quality, and dye lifetime. Final laser characteristics included a pulse energy of several joules in a stable, narrow ($\lesssim$0.1 nm) line.

In order to monitor the spectral distribution of the dye laser output on each shot, a spectrometer-television camera system was developed which revealed problems associated with fluctuating multiple output laser lines. This difficulty was solved by use of an additional prism in the laser system used for line narrowing, and by adherence to closer surface tolerances for all prisms used. Subsequently, the spectrometer-TV monitor was used in the acquisition of all Raman data, in order to insure that each laser shot had the required characteristics.

The method used for determination of the instantaneous (microsecond time resolution) space-resolved ($< 1\ mm^3$) temperature data was based on detection of the Stokes and anti-Stokes vibrational Q-branch Raman scattering intensities by individual photomultipliers contained in a polychromator housing of a 3/4-m grating spectrometer. The ratio of these signals is dependent upon temperature through the population factor for the first excited vibrational state of the test molecule, nitrogen. These data were achieved to a best final accuracy of about 5% by means of careful attention to a wide range of experimental difficulties, prominent among which was that arising from unwanted scattered light migrating into the optical detection system. Light baffling, use of optical cutoff filters, and modifications to the combustion tunnel window design (including use of an "open throat" configuration for a period of time) provided the required results. The

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**B.W. Gerhold participated in the thermocouple experiments.

relationship between the Raman signal ratio and the analytical expression leading to temperature determination was calibrated through use of a test medium of known temperature - namely, premixed hydrogen-air flames burned on a porous plug burner for which temperatures were accurately determined in previous experiments (many of which were carried out under earlier ONR sponsorship). The fluctuation values of temperature derived from the Raman data were determined at various flame radial locations at distances downstream of the fuel pipe tip corresponding to 1 to 100 tip diameters, and were presented in the form of histograms (probability density functions, or pdf's) as well as average values.

Following the successful implementation of temperature diagnostics, nitrogen density data were obtained through use of generally similar procedures, but with the added complexity of required <u>absolute</u> calibration of the Stokes Raman nitrogen channel used for the data acquisition (as opposed to the temperature measurements, for which the signals are <u>relative</u>, and for which the temperature calibration described previous applies to the <u>ratio</u> of Raman signals.) Substantial amounts of nitrogen density and temperature data were acquired in these experiments, which provided useful characterizations of the flames studied.

These experiments also showed that our method of data acquisition (photographic records of oscilloscope traces for individually-initiated experimental shots) was a strongly limiting experimental procedure. Additionally, the next phase of our work, involving the coupling of RS and LV apparatus, would require far more sophisticated experimental control. Thus, our next step was to change from manual RS data acquisition to a microcomputer-controlled digital data system, and to provide thereby for coupling to an LV processor.

In coupling the RS and LV probes into an integrated measurement system, the initial optical configuration was based upon only partly coincident test zones, which provided a limitation to the accuracy of the resultant temperature-velocity data. This was an experimental artifact, resulting from spatial limitations of the apparatus mounts, and was modified to a nearly completely coincident spatial test zone configuration in subsequent work.

The temporal simultaniety of the velocity and temperature data was initially characterized by a time delay of about 25μs between the LV and Raman signals, whch is a very small value from a fluid mechanic point of view. A time delay is required to permit the LV seed particle to leave the test volume before firing the laser source used for the Raman measurements (which would otherwise result in perturbation of the measurement volume conditions); the minimum magnitude, however, was limited here by the Raman laser source triggering characteristics. A somewhat smaller value was subsequently used when the initial Phase-R

Raman laser source was replaced by one produced by Candela Corp. For the velocity-temperature data obtained with our integrated probe system, the limiting measurement accuracy is inevitably that of the RS probe, for which about 5% was characteristic.

The last part of this experimental program, implementation of product gas (water vapor) density measurements was carried out in a newly-refurbished laboratory facility. A new fan-induced combustor of more sophisticated design was fabricated by Aerolab Corp. and was installed in our laboratory. This tunnel was designed for low initial turbulence level, excellent optical access (with a square 15cm x 15cm test section which permitted 1-m-long flat glass observation windows), and the ability to be moved in three dimensions. This last characteristic permitted us to rigidly couple the RS and LV probe optics on a steel table, ensuring an accurate and lasting alignment of their very small detection volumes.

In this part of the program, the density of water vapor was monitored for a variety of turbulent diffusion flames produced in the new tunnel by means of a new optical channel in the polychromator housing (i.e., additional to that used for the nitrogen Stokes and anti-Stokes channels required for temperature and nitrogen density data). Accurate placement of this exit slit and selection of an optimum spectral width for its pass band were required, because water presents some unique problems to Raman signal detection. Its vibrational Raman spectral bandwidth increases strongly with temperature, and is sufficiently broad at the highest temperatures encountered that it exceeds the widest possible practical slit width under these conditions. This, in turn, requires knowledge of the Raman spectral contour of this molecule as a function of temperature under these conditions, in order to make allowances for that part of the contour not detected at the known (from nitrogen Stokes/anti-Stokes data) temperature, because the desired water density information is related to the <u>total</u> water Raman signal (rather than just to that part viewed through a limiting set of slits). The correction involved is made more difficult by uncertainties in the fundamental energy level structure of the water molecule, which make uncertain any calculation of its Raman spectral contour. This problem was studied in this part of our program, and, by means of reasonable analytical assumptions concerning the unknown molecular characteristics and through use of several types of experimental calibrations, initial values of water vapor density data (in the form of pdf's at various flame locations) were obtained for the turbulent diffusion flames utilized.

Publications

The following is a list of publications supported in part by ONR that detail the research results described here.

"Raman Scattering Studies of Combustion," M. Lapp and D.L. Hartley, in _Combustion Measurements - Modern Techniques and Instrumentation_ (Proceedings of the Project SQUID Workshop on Combustion Measurements in Jet Propulsion Systems, Purdue University, 1975), ed. by R. Goulard (Academic Press, New York; Hemisphere Publishing Corp., Washington, DC, 1976), pp. 135-156. See also "Raman Scattering Studies of Combustion," Comb. Sci. Tech. 13, 199 (1976).

"Raman Band Contours for Water Vapor as a Function of Temperature," J.L. Bribes, R. Gaufres, M. Monan, M. Lapp, and C.M. Penney, Appl. Phys. Lett. 28, 336 (1976).

"Raman Scattering From Water Vapor in Flames," M. Lapp, AIAA J. 15, 1665 (1977).

"Raman Measurements on Flames," M. Lapp and C.M. Penney, in _Advances in Infrared and Raman Spectroscopy_, Vol. 3, ed. by R.J.H. Clark and R.E. Hester (Heyden and Son Ltd., London, 1977), Chapt. 6.

"Measurements on Turbulent Hydrogen Flames in a Circular Air Duct," J.C.F. Wang and B.W. Gerhold, AIAA Paper No. 77-48 (1977).

"The Study of Flames by Raman Spectroscopy," M. Lapp, in _Proceedings of the Sixth International Conference on Raman Spectroscopy_, Vol. 1, ed. by E.D. Schmid, R.S. Krishnan, W. Kiefer, and H.W. Schrotter (Heyden and Son Ltd., London, 1978), pp. 219-232.

"Instantaneous Measurements of Flame Temperature and Density by Laser Raman Scattering," M. Lapp and C.M. Penney, in _Proceedings of the Dynamic Flow Conference 1978_, (P.O. Box 121, DK-2740 Skovlunde, Denmark, 1979), pp. 665-683.

"Raman Scattering Measurements of Combustion Properties," M. Lapp, in _Laser Probes for Combustion Chemistry_, American Chemical Society Symposium Series Vol. 134, ed. by D.R. Crosley (American Chemical Society, Washington, DC, 1980), Chapt. 17.

"Temperature-Velocity Correlation Measurements for Turbulent Diffusion Flames from Vibrational Raman Scattering Data," S. Warshaw, M. Lapp, C.M. Penney, and M.C. Drake, in _Laser Probes for Combustion Chemistry_, American Chemical Society Symposium Series Vol. 134, ed. by D.R. Crosley (American Chemical Society, Washington, DC, 1980), Chapt. 19.

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